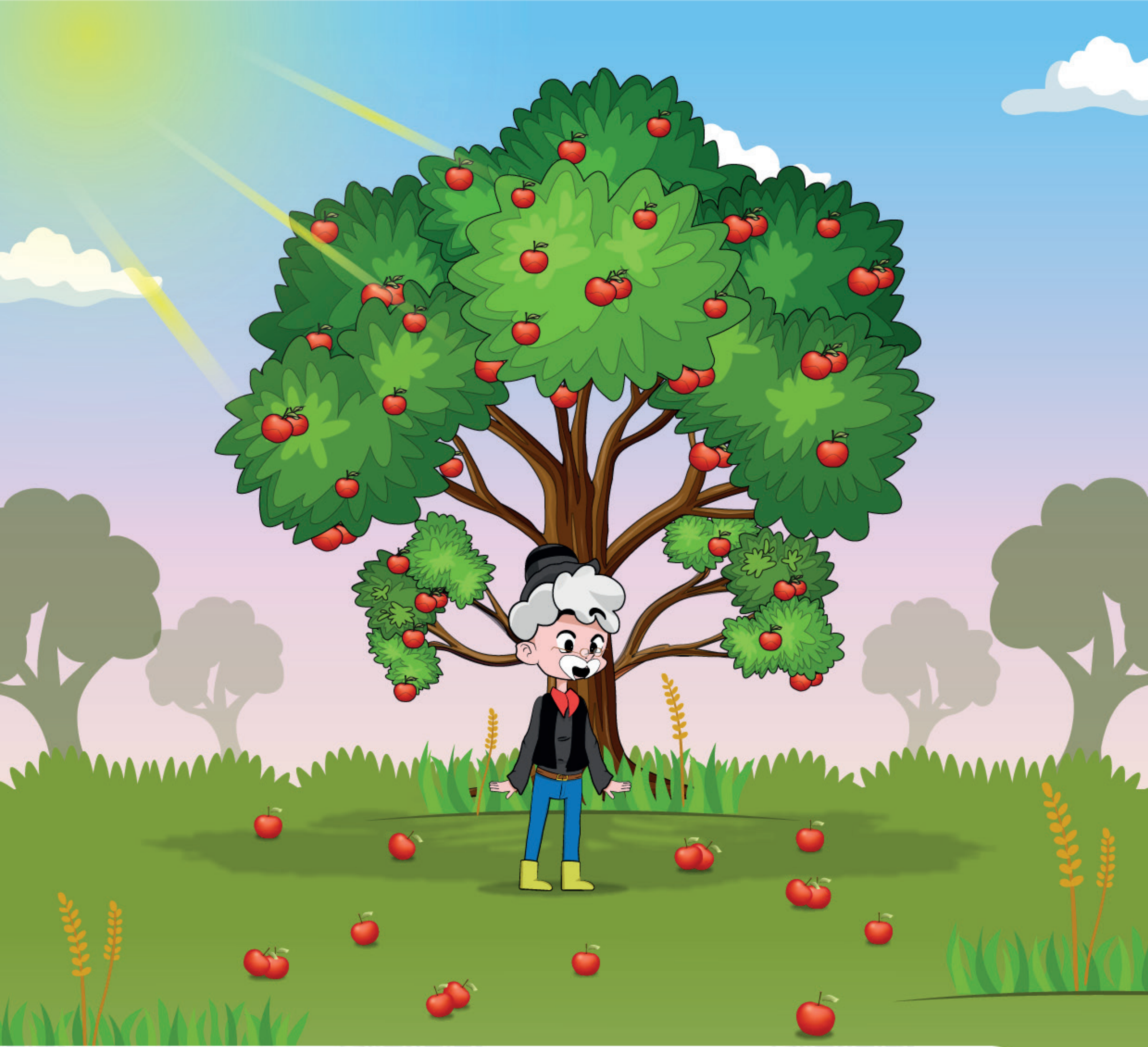


Part 1

MECHANICS: DYNAMICS

ARPHYMEDES

Christiaan Huygens (1629-1695)

Fig. 20

Laws ruling the elastic collisions.

Christiaan Huygens was a Dutch mathematician, physicist, engineer, astronomer, and inventor. He was regarded as one of the most important figures in the Scientific Revolution. He met other important scientists like Blaise Pascal, Gottfried Wiliam Leibniz and also Isaac Newton and discussed with them topics from mathematics and physics. Among other things, Huygens studied how things move and collide with each other. He disagreed with René Descartes's laws for the elastic collision of two bodies. Huygens found two unchanging aspects: mass times speed squared, and the velocity plus direction of a system's center of gravity.

Sir Isaac Newton (1642-1727)

His groundbreaking contributions shaped the foundation of modern science.

Sir Isaac Newton, an English physicist, mathematician, and astronomer, made significant contributions in the fields of motion, optics, gravity, and calculus. His ideas on light, motion, and gravity shaped physics for three centuries until Albert Einstein's theory of relativity brought modifications. Newton engaged in a heated dispute with Leibniz over the invention of calculus, causing a division within the scientific community. Today, both Newton and Leibniz are credited for their contributions to calculus, a branch of mathematics that helps us understand how things change in various fields such as physics, engineering, economics, biology, medicine, and more. Newton's curiosity led him to study alchemy, hoping to uncover nature's hidden laws, but his experiments with mercury, unaware of its toxicity, led to severe health issues.

Fig. 21

Gottfried Wilhelm Leibniz (1646-1716)

Fig. 22

A new theory called dynamics, based on kinetic energy and potential energy.

Gottfried Wilhelm Leibniz was a German polymath, active as a mathematician, philosopher, scientist and diplomat. He wrote works on philosophy, theology, ethics, politics, law, history and philology. Leibniz also made major contributions to physics and technology. He had ideas that later became important in areas like probability theory, biology, medicine, geology, psychology, linguistics and computer science. His computing machine, know as Leibniz Wheel was an early design for a mechanical calculator. Leibniz also had some interesting ideas about motion. He disagreed with other famous scientists like Descartes and Newton. He came up with a new theory called dynamics, based on kinetic energy and potential energy.

On this page you can find some proposals for projects that you can make at school or at home. There are even more on the accompanying webpage.

Project proposals:

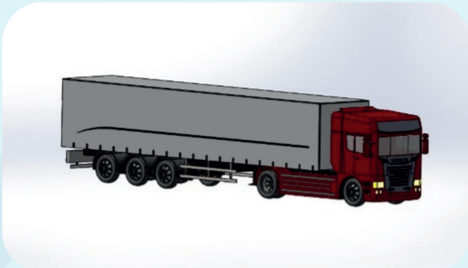
1. Try experiments using Newton's Law of Inertia offered in this chapter and then choose one you would like to perform.

2. Use the third Newton's Law.
- Hair dryer on a wheel cart.
- Two people with equal weight on two skateboards.
- Balloon rocket.

3. Make your own spring balance.

Technical application:

1. How do cars keep their balance on an inclined road



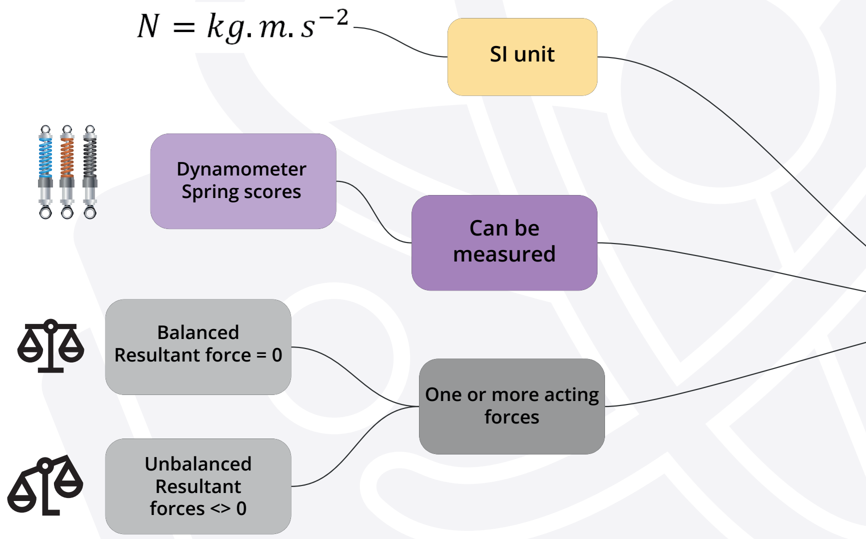
2. How do cars keep on the road at great speed and in a curve.

3. How a dynamometric wrench works.

Mechanics – Dynamics: What is force?

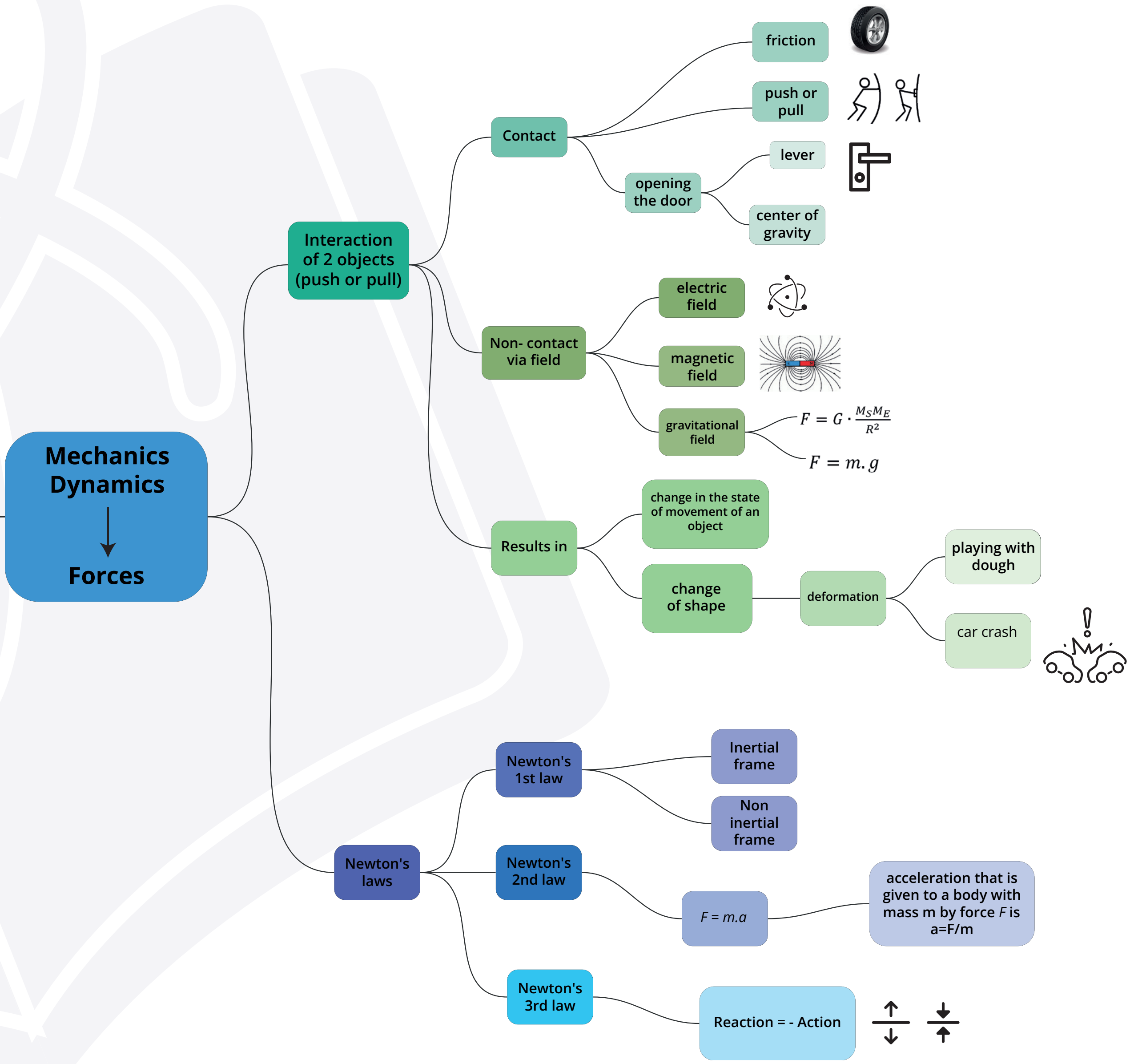
In this chapter we will continue to study mechanics. So far, we have described the state of motion by calculating velocity, distance, and acceleration. We have described situations when the state of the motion changes, but the reason behind this change remains unsolved. The concept we will deal with in this chapter is force. This chapter consists of the following parts:

- What is force?
- Moving or not?
- Newton's Laws
- Application of Newton's Laws
  - Force of gravity
  - Friction
- Physics on the playground and in space.
- Turning effect of force
- Center of gravity



In the first chapter on "What is physics" we were talking about the way scientists work. The first step is to observe. We perceive the world with our senses. The five common senses are vision, hearing, touch, smell, and taste. There is lot of physics, biology and chemistry behind understanding how our senses work. Our sense organs are mostly stimulated by waves. Our eyes are sensitive to visible light. Our hearing sense acoustic waves. Skin senses are mechanical in nature. These senses respond to pressure, bending, or other mechanical distortions of a receptor. We can think about it as push, pull or sometimes bend. We will start with our perceiving of acting force. Following examples will show you various situations in which Arphy can experience push or pull. Try to think before you watch the animation to test your intuition.

The Mind map shows what we will deal with in this chapter. It is all about forces. What is force, how do we perceive it by our senses, what are the impacts of acting force(forces), what laws and tools we use to do the calculations, what is the SI unit.



We will start with our perceiving of acting force and explaining the interactions, to understand the connection between the movement and the force. We will study Newtons laws and continue with their applications. We will go step by step using videos and animations and when possible, we will offer ideas for your own projects and present technical applications.

Example 1.

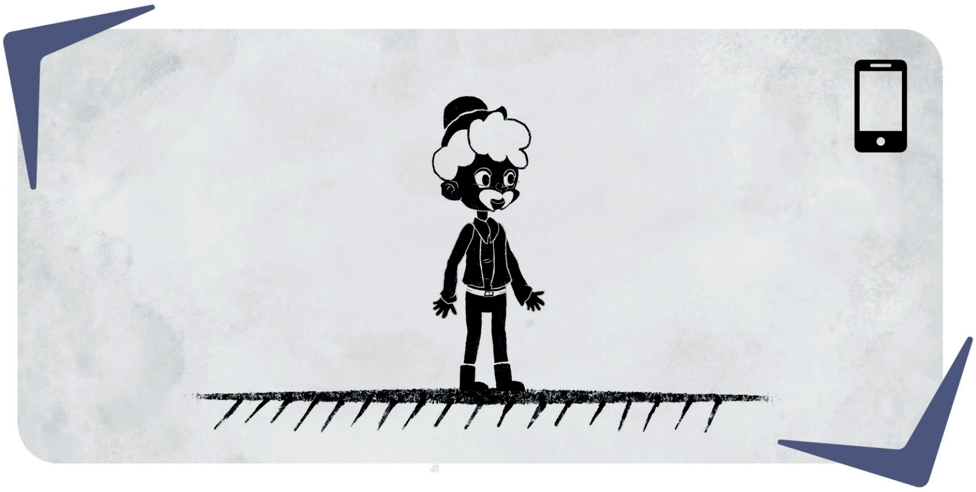
There is Arphy standing on the floor.
What do you think? Does Arphy feel any push or pull? The answer is in the animation. The fact that we stand is a daily experience, our senses perceive it, but our brain no longer evaluates it. This situation does not pose any risk.

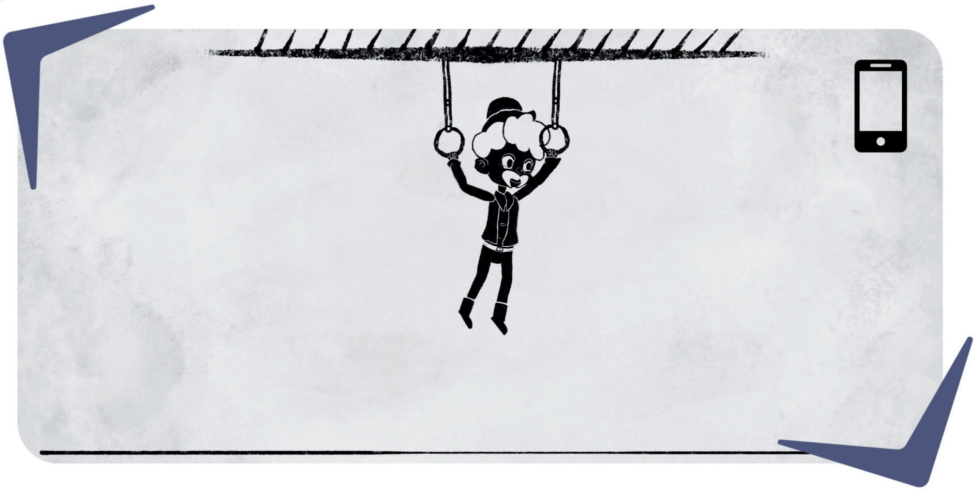
Your comments, question, observations.

Example 2.

In this example Arphy goes to the gym and is hanging on the gymnastic ring. This is not what he does daily. What does he feel in his arms? What happens if he doesn't stick anymore?

Your comments, question, observations.





Example 3.

In examples 3 and 4, Arphy's friend exerts a force on him. What will happen to Arphy?

Your comments, question, observations.

Example 4.

After watching this animation think about the differences that you have observed in those two situations.

Your comments, question, observations.

Example 5.

Arphy kicks the ball on quite different surfaces on the grass and on the parquet floor. The questions are:
Why did the ball start movement?
Why didn't the ball stop in the same distance?
Watch the animation.

Your comments, question, observations.

Example 6.

Arphy is sitting in a car moving in a straight line and hits the standing van, without breaks. In our animations nothing happens to Arphy, concentrate only on cars. After watching the animation answer the following questions.
What happened to the cars? Did they move and how?

Your comments, question, observations.

Example 7.

We have now changed the situation: Arphy is sitting in a car moving in a straight line and hits a smaller car that is standing still, again without breaks. After watching the animation answer the same questions.
What happened to the cars? Did they move and how?
How do your answers differ for these two collisions?

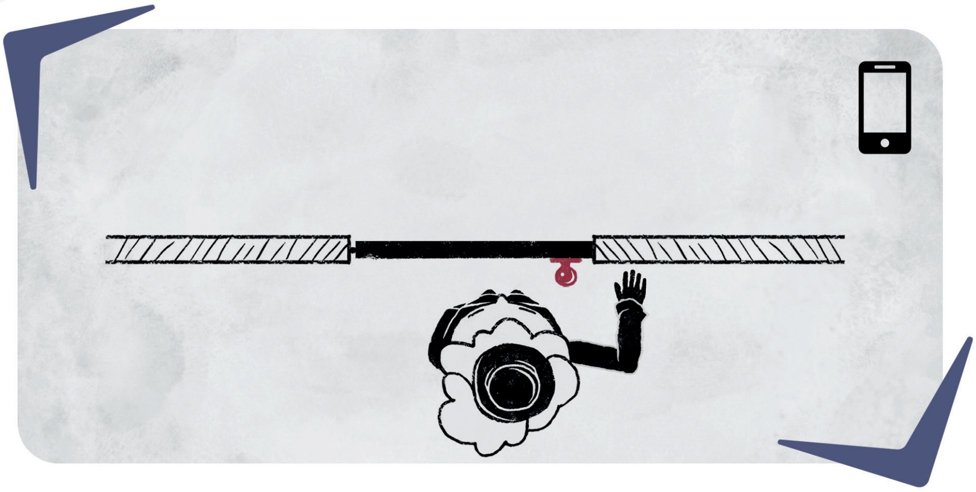
Your comments, question, observations.

Example 8.

Arphy is opening the door with the doorknob at different distances from the axis of rotation. After watching the animation, answer the following questions:
Where would you put the doorknob to open so that the door opens as easily as possible?
You can also try it by pressing on the door while opening it at different distances from the door frame.

Your answer, comments, question, observations.

In all cases there was one common factor – push or pull. This is how we describe so called force acts on objects.



Force & motion sort

In the picture bellow, there are various activities: Sort them into the following table "Push" and "Pull".

Sort Pull

Sort Push

Fig. 24

Fig. 25

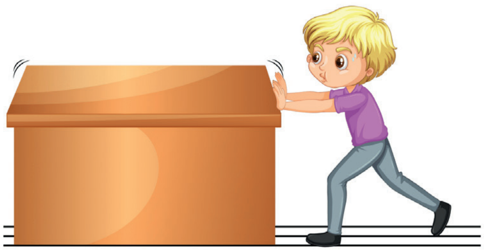


Fig. 26

Fig. 23

PUSH	PULL

Based on all what you have seen so far, we can say that force is the measure of interaction. In our cases there was a mutual contact, but this can happen also via the presence of a field, such as magnetic, electric or gravitational one.
Following are examples of these interactions.

Magnetic field

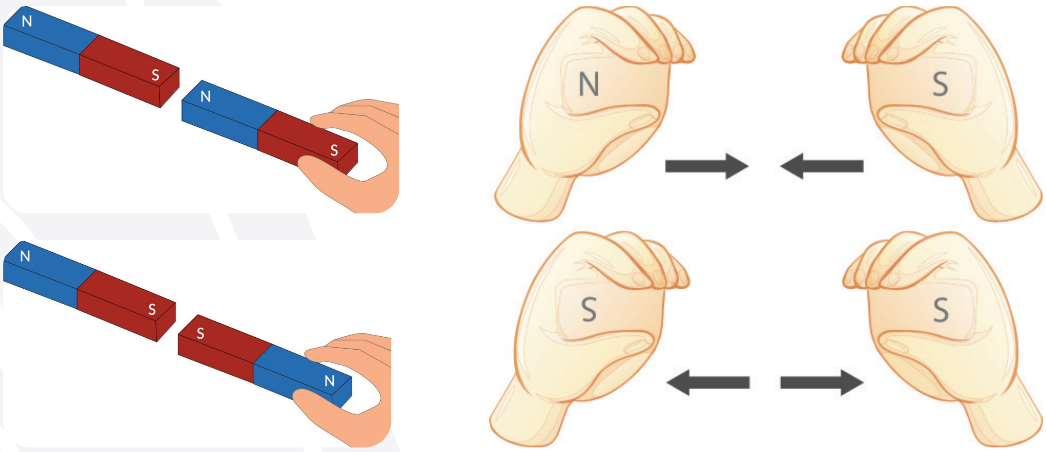


Fig. 28

Electric field

Gravity

Fig. 27

Mutual contact can also cause deformation, but in our examples, we suppose having only rigid body which does not deform or deformation is so small that it can be neglected.

Mechanics vs. Dynamics: Moving or not?

Let's have a short travel in the past discoveries: The animations in the previous part showed possibilities of different outcomes of an acting force on an object. Since Aristotle (384-322 B.C.), the change in the motion was sometimes observed and scientists were thus interested in a relationship between the force and the motion. To Aristotle, the natural state of an object was at rest, and a force was believed necessary to keep an object in motion. Furthermore, Aristotle argued, that the greater the force on the object, the greater is its speed.

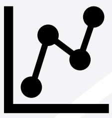
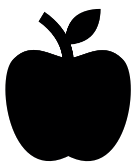
Some 2000 years later Galileo disagreed: He maintained that it is just as natural for an object to be in motion with a constant velocity as it is for it to be at rest. Galileo started to do some experiments and observations on this subject.

The relationship between the change of motion and a force was finally described by Sir Isaac Newton (1642–1727). He belongs to the greatest physicists of all time. Newton was raised up by his grandparents in the countryside where he can do a lot of experiments. His mother widowed very soon, then she married again, and Isaac went to live with his grandparents. His mother wanted him to become a farmer, but his interest was in studying.

Galilei's experiment was based on observations, he was then imagining extreme situations.

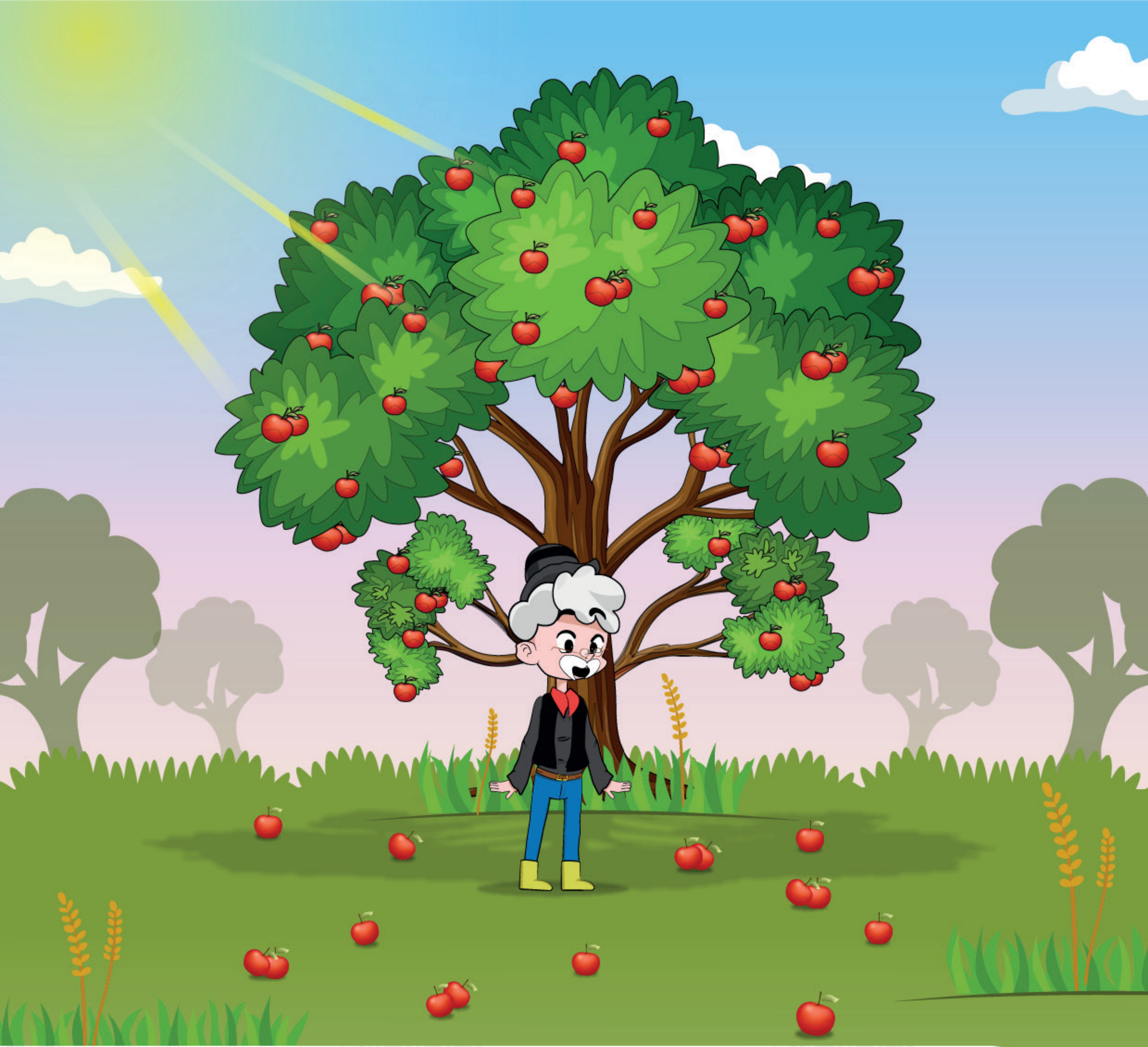
He proceeded as follows. Imagine:

1. To push an object with a rough surface along a tabletop at constant speed requires a certain amount of force.
2. To push an equally heavy object with a very smooth surface across the table at the same speed will require less force.
3. If a layer of oil or other lubricant is placed between the surface of the object and the table, then almost no force is required to move the object.
4. Notice that in each successive step, less force is required.
5. As the next step, he imagined that the object did not rub against the table at all - or there was a perfect lubricant between the object and the table - the object would move across the table at constant velocity with no force applied.
6. A steel ball bearing rolling on a hard-horizontal surface approaches this situation.

Isaac Newton	Isaac Newton - Physics	
Mathematics 	Motion	 
Physics 	Gravity	
Chemistry 	Light	

Newton became a student at Cambridge University, but when a plague outbreak struck in 1664, the university was forced to close for 18 months, something similar to the Covid-21 outbreak in our times. Newton retreated to the country, where he discovered the Laws of motion, gravitation and invented the mathematical basis of calculus. And that was it, at the age of 22 he did the most important stuff in his life.

He is considered the greatest scientists of all times because he figured out the need to discover - not only to describe what has happened, but also to find out why. Thanks to him, we use mathematics as a language for describing physics. He demonstrated that with the right description at the right moment, we can describe the future.



Part 2

MECHANICS: DYNAMICS

ARPHYMEDES

Mechanics – Dynamics: Newton's Laws

NEWTON'S FIRST LAW

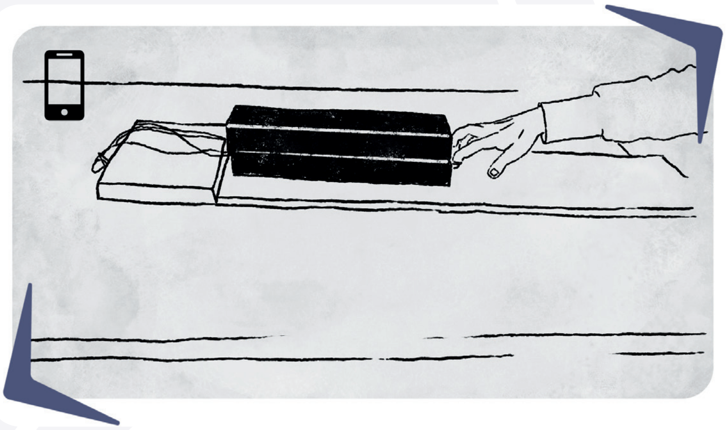
In the 17th century, Newton came up with the three basic ideas that are applied to the physics of motion of most objects of size to these days. His ideas were tested and verified. They only started to break down when scientists started to investigate objects moving at the speed of light, very small particles inside the atoms, extreme temperatures, or when the interacting objects are huge, like galaxies.
The first Newton's law states that an object at rest tends to stay at rest, and an object in motion tends to stay in motion, with the same direction and speed unless a force pushes or pulls it.
This tendency of an object to maintain its state of rest or of uniform motion in a straight line is called inertia. As a result, Newton's first law is often called the law of inertia.

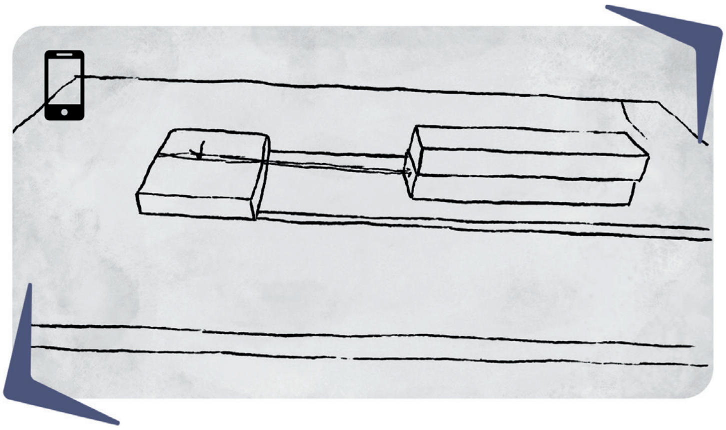
Now try this law for yourself: Follow the movement of two wooden blocks in the video. One of them is connected with a rubber band to one side of the wooden board.
At first the two blocks are placed loosely on the top of each other. If we pull the lower block and release it, the lower block will move, while the upper one will remain more or less at place.

When the upper block is fixed to the lower one, and we pull the lower block again and release it, so something different happens. The blocks hits a stop. The lower block remains stationary and the upper block moves on because of inertia.

Newton himself said that his laws were based on the foundations of his predecessors, one of whom we have already mentioned: Galileo Galilei. He imagined and idealized world - a world without friction - and he recognized that it could lead to a more accurate and richer understanding of the real world.

In physics we often simplify our observations, for example when studying how multiply forces act on several objects. We try to neglect some factors. For example, we neglect the size of objects, or consider them to be perfectly rigid, or we neglect the friction. But we must be careful in which situations we do it. For example, when jumping with a parachute, in the absence of friction, we would kill ourselves. Also, a race car designers know how important the friction is and that cars are not unbreakable, etc.





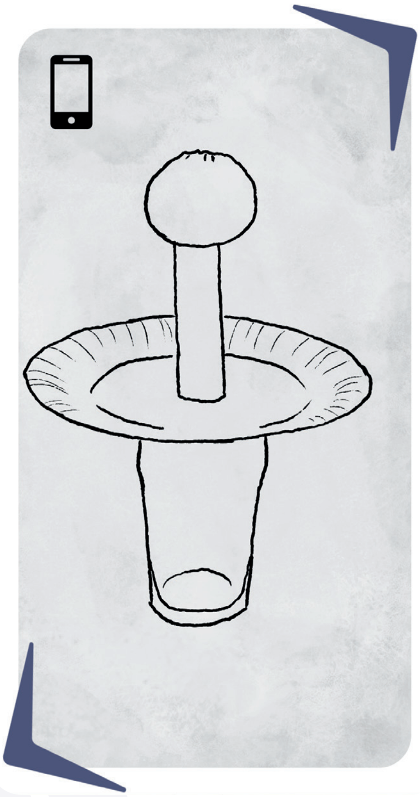
Some experiments using Newton's first law look like a magician trick. You can watch one in the video: an effective trick could be done with the tablecloth. Pull out the tablecloth really quickly and the plates and glasses remain on the table.

Project proposal.

To perform the experiment, you will only need 0,7 l plastic bottle.
Procedure:
Place a full bottle of water at the corner of the table. First try it with the closed bottle, then, when you have trained enough, leave it open. Tie one end of a regular thread to its throat.

1. Pull the thread slowly.
When the thread is pulled slowly, the bottle will react and tip over. Why did it happen?

Your comments, question, observations.



The described experiment can be performed even under more severe conditions. In this case, we first place a can of juice on the corner of the table and place the water bottle up to its upper base. Then we perform a similar experiment as in the previous case. However, the jerk must be fast and "hard". We achieve it by winding the free end of the thread on a pencil and holding it in our hand. We jerk the hand so that the thread does not rest on the fingers of the hand. These could dampen the jerk, which is undesirable.

2. Pull the thread quickly.
With a very fast tear, the thread breaks, but the bottle does not even move. can you explain it?

Project proposal.
Write your own experiment using Newton's first law.

1. Make research: in books, on the Internet and choose one. Do not forget to write down the source.
2. Make a list of what you need.
3. Note down the procedure.
4. Conduct the experiment.
5. Present the experiment to your classmates or make it at home and let your parents make a video of it.
6. What was the trickiest part? What have you learned?

Your comments, question, observations.

Your comments, question, observations.

The chosen experiment is from:

Materials needed:

Sketch of the experiment:

Procedure:

NEWTON'S SECOND LAW

The history of laws of motion goes back to Greek philosopher Aristotle (384 -322 B.C.). His views on motion were widely accepted because they were supported by observations in nature. He stated that to keep something moving a force must be constantly applied. He also thought that the weight can affect falling bodies.
His views were challenged for the first time in the 16th century when Nicolaus Copernicus published his Sun-centered model of the universe. Aristotle's opinion was that the Sun, the Moon and the planets all revolved around the Earth. Although Copernicus Sun-centered model was not a topic of mechanics of motion, the heliocentric cosmology described by Copernicus revealed the vulnerability of Aristotle's science.

Galileo Galilei was the next one who challenged Aristotle's ideas. His experiments with falling objects proved that Aristotle's conviction that weight affected falling objects was wrong.

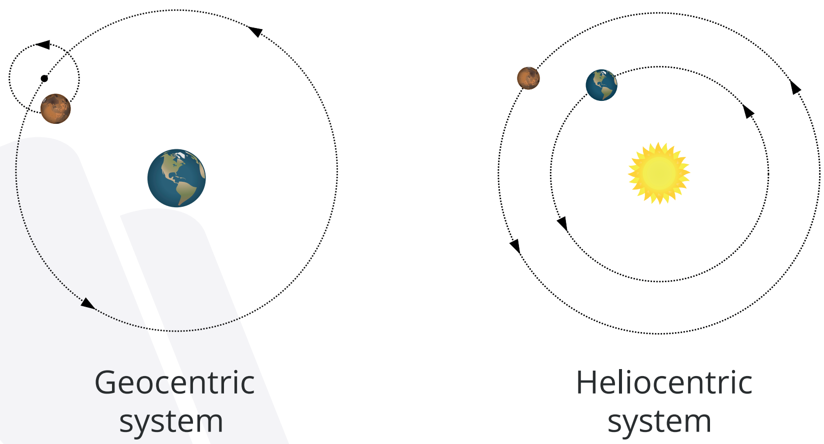
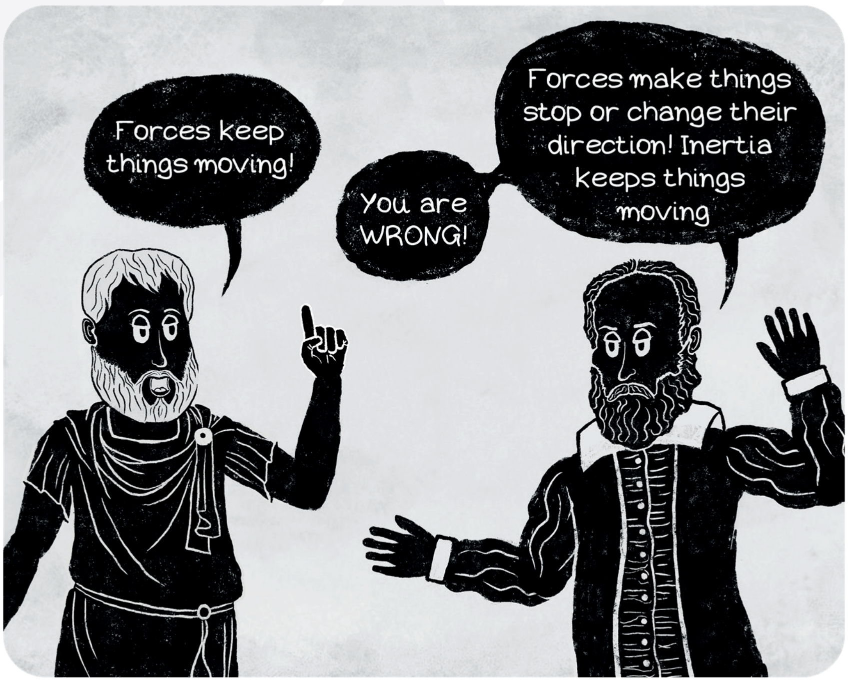

Geocentric system
Heliocentric system

Fig. 29


Forces keep things moving!
You are WRONG!
Forces make things stop or change their direction! Inertia keeps things moving

But it was René Descartes, who developed Cartesian coordinate and who thus shifted the understanding of a motion. He proposed three laws of nature. He claimed that each object always remains in the same state and that consequently, when it moves, it continues to move along straight lines. Newton clearly studied Descartes.

Newton's second law states that when there is a change in the speed of an object or if the moving object changes the direction, the reason behind is an external force.

Force – ***F,*** SI unit is Newton - symbol N.

We write the Newton's second law in the following form: $F=m\ a$, units $N=kg.m.s^{-2}$

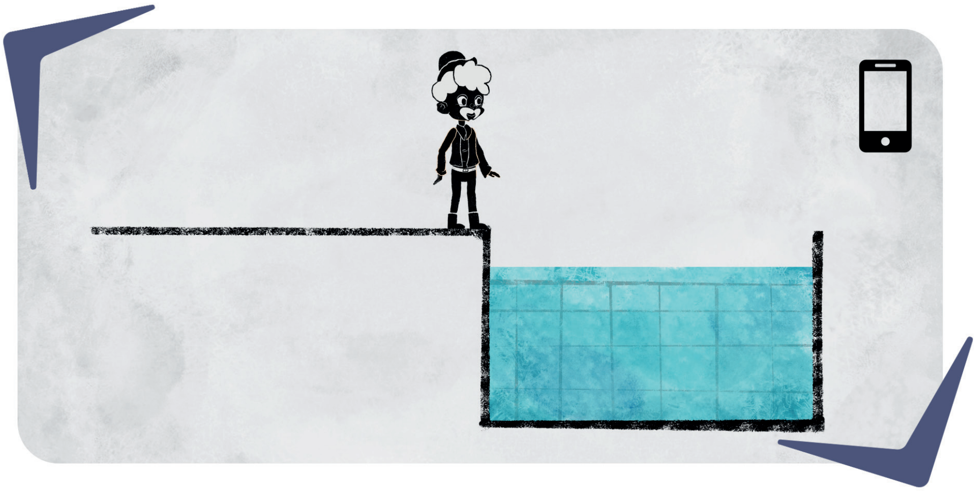
Newton's second law states that when you push or pull something, how much it speeds up (accelerates) depends directly on how hard you push or pull (the force), and indirectly on how much mass the thing has. If you push or pull in a certain direction, the thing will speed up in that same direction.

Force and acceleration are quantities for which we need to know not only magnitude but also the direction. For such cases we use **bold** characters in the equation. Or we can use a plus or a minus sign (as we did in kinematics already). We can write it without marking them. There are some examples on the following pages to help you grasp this Newton's law. In the animation you will see Arphy at the edge of the pool. The direction of the force (push or pull) makes a huge difference.

Watch the animation, according to the direction of the force Arphy gets either completely wet, or he will stay safely outside the pool. We have already had examples with push or pull, but we focused primarily on how we perceive the action of force.

What about the Newton's second law in our life?
Let's calculate the acceleration in different situations in animation with Arphy pulling a sledge.
Arphy is pulling a sledge with a force of 100N, while the mass of a sledge is 50kg.
Q: What is the acceleration of the sledge?
A:

$$\boldsymbol{a} = \frac{F}{m} = \frac{100\ N}{50\ kg} = 2\ \frac{m}{s^2}$$



Now we have 2 Arphies pulling a 50 kg sledge in the same direction.
Q: What is the acceleration of the sledge?
A:

$$a = \frac{F}{m} = \frac{200\ N}{50\ kg} = 4\ \frac{m}{s^2}$$

What if Arphy is pulling a 100kg sledge.
Q: What is the acceleration of the sledge?
A:

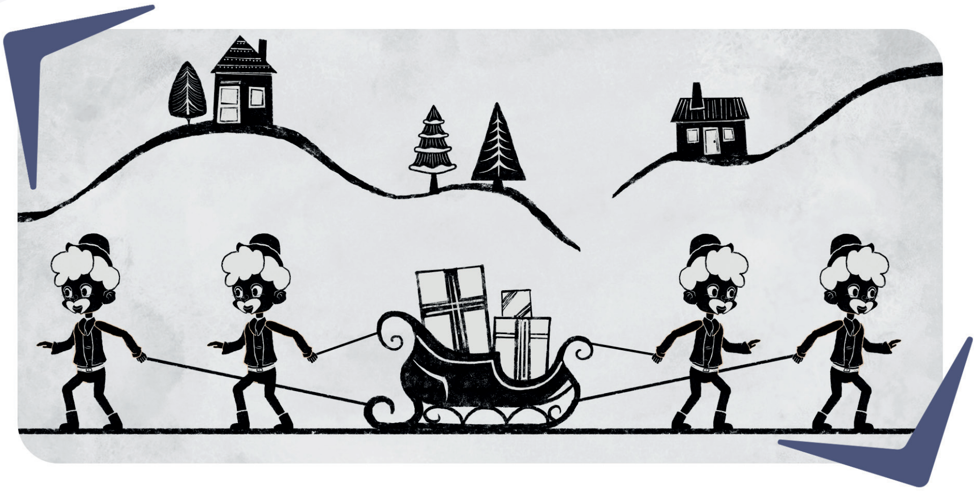
$$a = \frac{F}{m} = \frac{100\ N}{100\ kg} = 1\ \frac{m}{s^2}$$

Now, we have 2 Arphies pulling a 100kg sledge in the same direction.
Q: What is the acceleration of the sledge?
A:

$$\boldsymbol{a} = \frac{F}{m} = \frac{200\ N}{100\ kg} = 2\ \frac{m}{s^2}$$

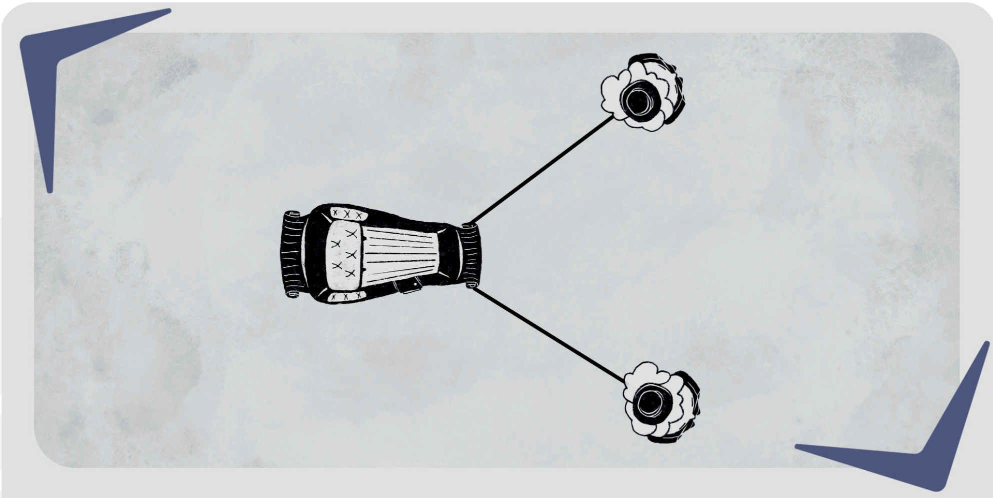
In another situation we have 4 Arphies pulling a 100kg sledge in an opposite direction.
Q: What is the acceleration of the sledge?
A: Remeber that we must also take direction into account.

$$\boldsymbol{a} = \frac{F}{m} = \frac{200\ N - 200\ N}{50\ kg} = 0\ \frac{m}{s^2}$$

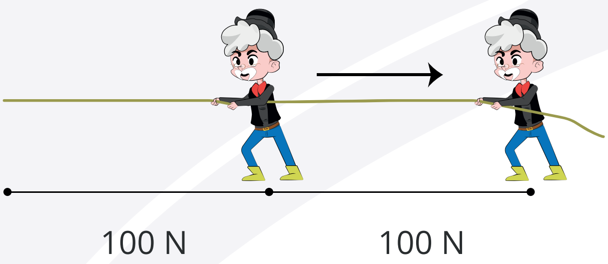


We will make another modification. 2 Arphies are pulling a 100kg sledge with forces forming a certain angle.
Q: What is the acceleration of the sledge?
A:

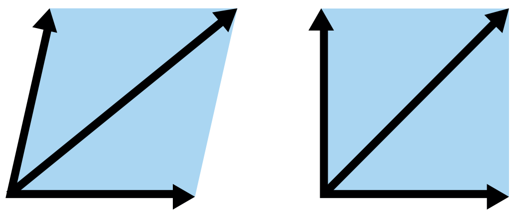
From experiments you have seen in the animations we can conclude that the Newton's second law concerns the net (total) external force. The net force is the sum of all forces acting together on the object with their magnitude and direction. Animations and pictures will help us to understand that.



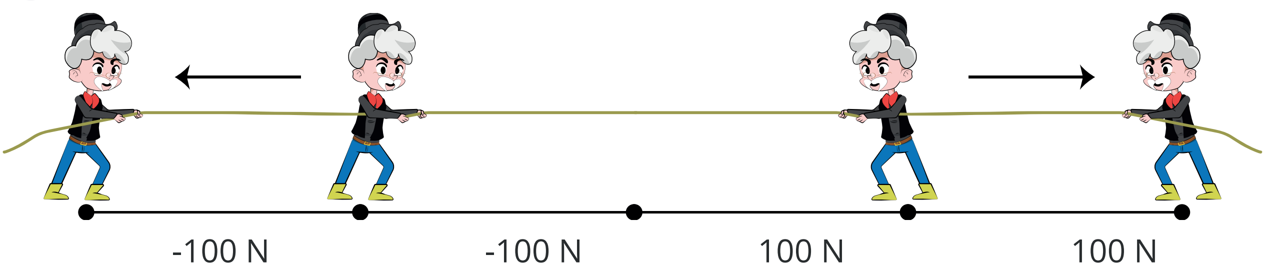
200N - Resultant (Net) force



Resultant (Net) force depends on the angle.



Resultant (Net) force = 0



To understand the difference between an external and an internal force the next animation will help. When Arphy pushes the car from outside, he applies an external force and the car starts moving. However, when sitting in the car, Arphy can push the steering wheel as much as he can, but nothing will happen. The car will not move because pushing the steering wheel is an internal force.

To sum up: knowing the change of velocity, we know the acceleration and we can predict where an object will be at a certain time in space. Knowing all the forces acting on a basketball (including friction of the air) we can calculate whether the player will score or not.

NEWTON'S THIRD LAW

The Newton's third law states that for every action (force) there is an equal and opposite reaction (force). If you push an object, that object pushes back in opposite direction equally hard. Forces are found in pairs. The recoil of a cannon when firing a cannon ball is one demonstration of action-reaction forces you might have seen in many historical films. When a cannon ball is fired from a cannon, the cannon moves backwards. We used the picture of the Da Vinci's cannon as an example.
Task: Give at least 3 other examples.

Your comments, question, observations.

Which one of the forces is regarded as "action" and which one as "reaction" is not relevant. Furthermore, although these action and reaction forces are of equal magnitudes, they act on different bodies and their effects are quite different, depending on the masses of objects.

Reaction forces exist even if the two interacting bodies are not in direct contact, so the forces between them must bridge the intervening empty space. This is the case of two magnets (magnetic field), electrical charges (electric fiels), or objects in the gravitational field. Even if it does not look like it, we meet with such forces daily.

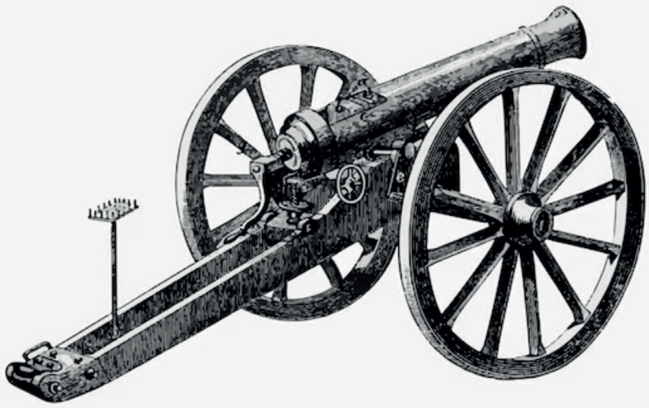


Fig. 30

Let us now calculate the action reaction force between the Earth and an apple. We will consider an apple in a free fall from some height above the ground. The Earth pulls on the apple by means of gravity. If this pull has a magnitude of, let's say 5 N, then the Newton's Third Law implies that the apple pulls on the Earth with an opposite force of 5 N.

This reaction force also applies to the gravity—it is the gravity that the apple exerts on the Earth. However, the effect of the apple on the Earth is insignificant because the mass of the Earth is so large that a force of only 5 N produces only a negligible acceleration of the Earth (a = 8×10^{-25} m/s^2).

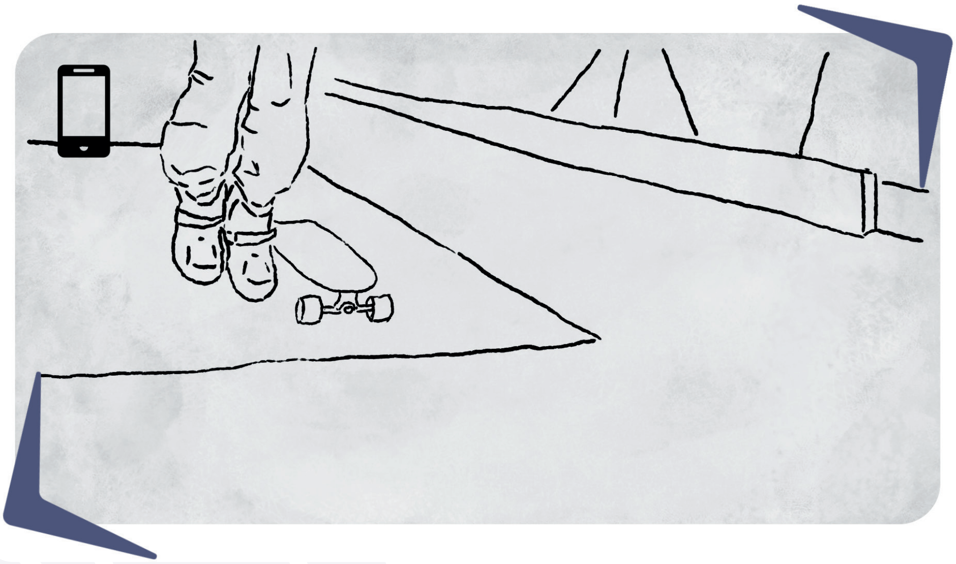
When Arphy walks, he pushes the ground, and the gound pushes back – this is also an example of an action and the reaction. The ground pushes back on him, so there is a force, which according to the second law gives him acceleration but at the same time there is a friction force in the opposite direction and so according to the first law (inertia) he walks more or less with the same velocity.

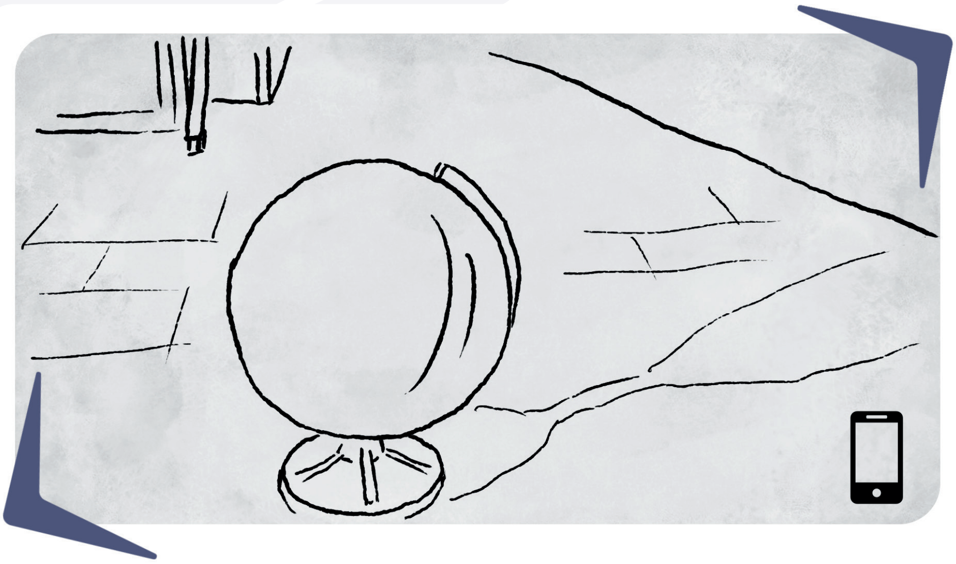
The same goes for jump. When we jump we are pushing the earth backwards for us to go forwards. (When something moves forwards there must always something move backwards). Watch the jump video. When trying to jump forward while on a skateboard we could not make it. Why?

Your comments, question, observations.

Watch the video with a toy car spinning a globe. Again, to be able to move forward something must move backwards. But the globe is not stable and the car just spins it.

Your comments, question, observations.





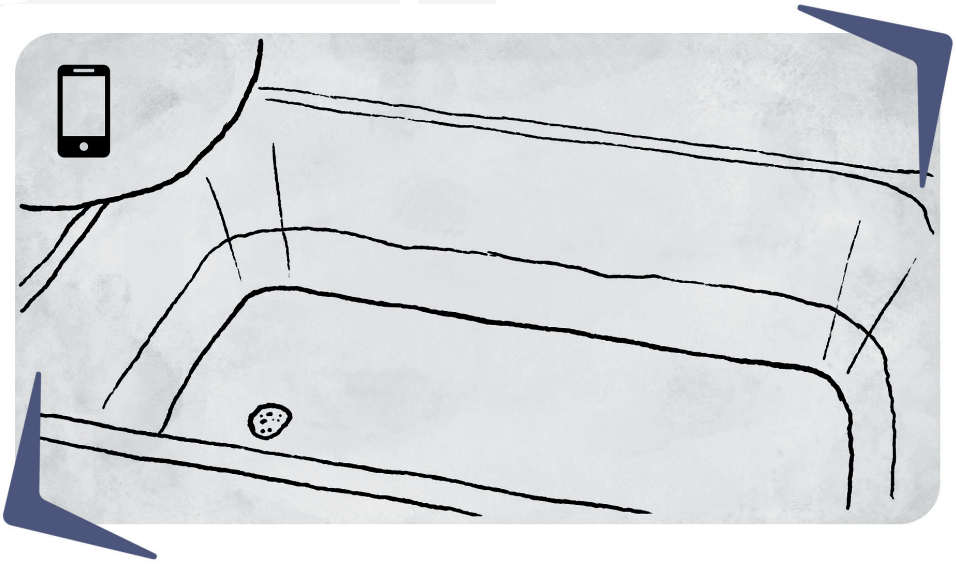
The same goes when the toy car moves on a cardboard block supported by pencils. For car to move forwards block moves backwards.

Your comments, question, observations.

The Newton's third law is present everywhere. We can find interesting examples in animal kingdom. Jet propulsion involves a forcing substance through an opening at high speed. To travel by jet propulsion, a cephalopod such as a squid or octopus will fill its muscular mantle cavity (which is used to get oxygenated-water to their gills) with water and then quickly expel the water out of the siphon. Because the animal exerts a force on the water jet, the water jet exerts a force on the animal, causing it to move.
Quite new research from the year 2021 showed that butterflies also use jet propulsion for their flight (https://www.snexplores.org/article/butterflies-use-jet-propulsion-for-quick-getawaysshowed).

Butterflies do not belong to a species we would call strong fliers. When they fly it looks more like flutter. At the same time this hardly predictable move makes it hard for predators to catch them. If you have ever tried to catch a resting butterfly, you certainly agree. Butterflies clap their wings above their bodies during takeoff. The wing clap forms a pocket of air that shoots out like a jet.

If you look on the Internet for the movement of the Silver-washed Fritillary you can find video showing this extraordinary use of jet propulsion. This butterfly moves upward when its wings move down and forward when they clap.
In technical application jet propulsion is mostly used in aircraft and rocket engine, but it can be applied to jet propulsion for small, high-speed boats and pleasure craft.
In the video you can watch the boat powered by air jet from a balloon.



Your comments, question, observations.

With the following rap you may remember the laws easier.

"Sir Issac Newton in the time of plaque, was studying at home,
corona made you do the same with your iPhone.
He stated the laws, so listen to them,
Learn and enjoy the pure beauty of them.
First Newton's Law simply states,
Every object will remain in the unchanged state,
Either at rest or uniform straight-line motion,
Unless compelled to a different state,
The reason for which is called external force.
Things are lazy, do not want to change their doing.
Inertia is what we are accusing.
The second one says how velocity changes,
Force equals mass times acceleration,
Formula used for such situation.
The third law says that for every action,
There is an equal and opposite reaction.
Hitting the wall made of brick will show you the trick.
With a force that responds just as quick.
Now use the force of your mind to keep the knowledge Newton found."

Project proposals:

1.Hair dryer on a wheel cart.

Materials needed:
Hair dryer, skateboard and something to attach the hair dryer to the skateboard, extension cord.
Procedure:
Attach the hair dryer in such a way that air is blown in the imaginary axis between the wheels of the skateboard. Take care, because you can let it move only to the length of extension cord.
Ask your classmate to record the experiment.

2.Two people with equal weight on two skateboards.

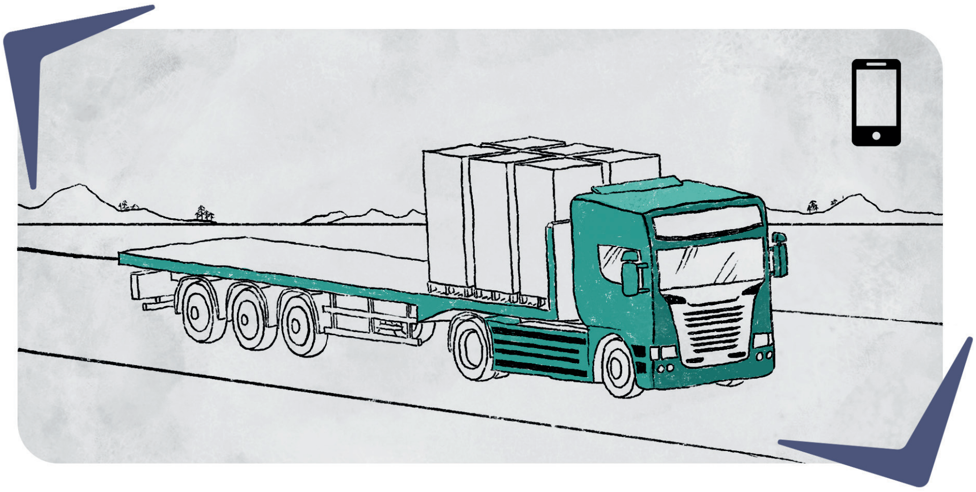
Materials needed:
Two skateboards and two volunteers.
For safety reasons, use elbow and knee pads with your helmet.
Procedure:
Both volunteers stand on skateboards, close to each other facing each other.
If one volunteer pushes – both move with the same velocity, but opposite direction.
Ask your classmate to record the experiment.

3. Balloon rocket

Task: Make a balloon rocket to understand Newton's third law.
Materials needed: 1 balloon, 5 m string, 1 drinking straw, cellotape.
Procedure:
1. Pass the string through the straw
2. Tie the ends of the string to two chairs.
3. The string must be tightly stretched.
4. Blow up the balloon and then held its mouth, so that no air escapes from it.
5. You will need a help of your classmate to tape the balloon with the straw.
6. Now you are ready to leave the mouth of balloon and watch the rocket slide over the string.
7. The air blows out in one direction and the rocket slides in the other direction.

On the last page you can find two 3D models mentioned later in this chapter.

3D model of a standing truck on a differently inclined road.



3D model of a truck entering the curve with a different speed.